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Bragg Grating Simulation Software

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ABSTRACT (U)

This document is a user manual for a software application that predicts the complex reflection spectrum of fibre Bragg gratings, given user defined input parameters. The software is designed primarily to complement the joint DSTO/Swinburne grating writing facility (FigFab) and can be used to determine the optimum writing variables to achieve a required grating reflection profile. Alternatively the software can be used to simulate the intensity and phase information for use in other Bragg grating sensing applications such as intragrating strain profiling.

RELEASE LIMITATION

Approved for public release

APPROVED FOR PUBLIC RELEASE

Bragg Grating Simulation Software

Executive Summary

In recent years, there has been a growing requirement for Bragg grating sensors to support a number of widely differing tasks across several divisions in the DSTO. This requirement had previously been met by outsourcing to commercial companies. However in 2002, the DSTO invested in a research capability located at Swinburne University of Technology, which now allows DSTO staff to fabricate their own gratings to specific requirements.

This document is an operation manual for custom-designed simulation software to predict the performance of fibre Bragg gratings, given user defined input parameters. The software is designed primarily to complement the joint DSTO/Swinburne grating writing facility (FigFaB) and can be used to determine the optimum writing parameters to achieve a required grating profile. Alternatively, the software can be used to simulate the intensity and phase information for use in other Bragg grating sensing applications such as intragrating distributed measurements.

Contents

1. Introduction

This document is a manual for operation of custom-designed simulation software for the prediction of the complex reflection spectrum of fibre Bragg gratings, given user defined input parameters. The software is designed primarily to complement the joint DSTO/Swinburne grating writing facility (FigFab) and can be used to determine the optimum writing parameters to achieve a required grating profile. Alternatively the software can be used to simulate the intensity and phase information for use in other Bragg grating sensing applications such as intragrating strain profiling.

The simulator can be installed on any computer as an executable file. Because the simulation process requires as input data gathered from experimental calibrations from the FigFab grating writing laboratory, it is recommended that the user ensure that the latest calibration files are installed.

2. Basic Operation (Quick Start Guide)

2.1 Setting Parameters

The parameters for the simulation are set using the controls arranged on the left side of the screen. The main parameters which need to be set are the laser power, the writing speed, the length of the grating, the fibre type and the apodization profile.

Depending on the bandwidth of the resultant grating the wavelength range may need to be altered in order to view the complete spectrum. More details on individual parameters can be found in the Simulation Parameters section of this document.

2.2 Running the Simulation

To simulate the reflection spectrum of a grating, click the Simulate button on the left, under the simulation parameters. If the reflection spectrum is not of interest then it does not need to be calculated (by un-checking the Simulate Reflectance box), greatly reducing the simulation time. This may be useful when only examining apodization or other profiles along the grating, rather than the reflection spectrum of the grating.

2.3 Simulation Accuracy

The accuracy of the simulation is controlled by the settings in the Simulator Parameters section. The Wavelength Step parameter sets the resolution of the simulated reflection spectrum. Decreasing this value will provide a more detailed output but will cause the simulation to take longer to run. This setting has no effect on the grating profiles.

The Grating Length Step parameter sets the size of the sections the grating is broken into to be simulated. It is not a physical characteristic of the grating but rather a parameter required by the computational approach. Changing this value will directly affect the resolution of the grating profile graphs. However this parameter has a different effect on the reflection spectrum. An accurate reflection spectrum can be generated from what appears to be a rather coarsely defined grating coupling-coefficient profile. The coupling

coefficient is a complex number with an absolute value equal to the refractive index envelope and an argument which is dependent on the grating phase.

Increasing the Grating Length Step parameter too much may result in multiple copies of the reflection spectrum being displayed in the output due to an artefact in the algorithm. These copies always exist but the distance between them and the main reflection increases as the step parameter is reduced.

Figure 1 shows a simulation result where multiple copies of the reflection spectrum are displayed because the grating length step was too high.

Decreasing the Grating Length Step will often have little effect beyond a certain value. This value will depend slightly on the complexity of the grating's pitch and index profiles and the steepness of the apodization profile. For most standard unchirped gratings, there is little improvement below a 50 µm grating length step.
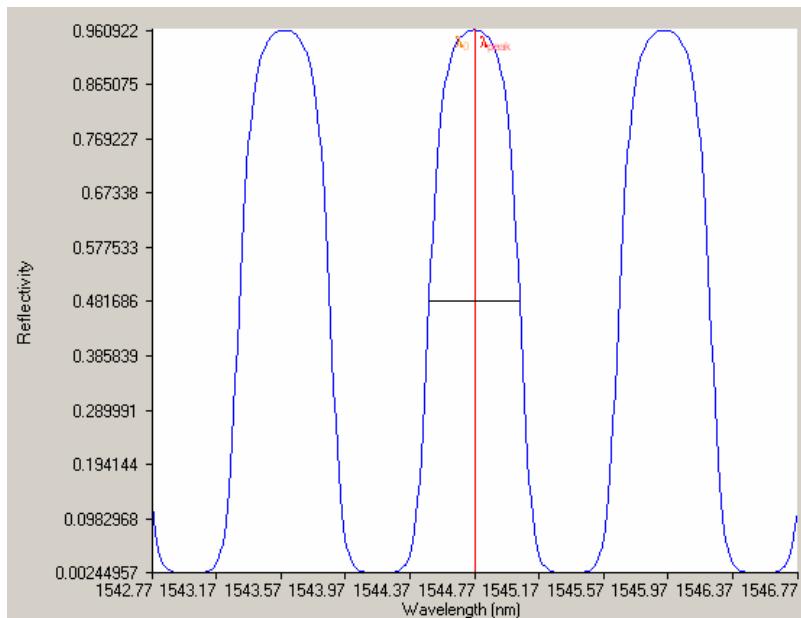
Figure 1: Multiple reflection peaks in the reflection spectrum window indicates a too high Grating Length Step has been selected

2.4 Displaying Results

The results of a simulation are displayed in graphical format in the main application window. More information on this display is provided in the next section.

The data displayed in the graph can be chosen from the Graph menu. There are two main categories of graphs; grating profiles and reflection spectra. More information about each type can be found in section 3.1.

2.5 Saving Data

The data displayed on the graph can be saved using the Save Graph Data… command in the File menu. Data is always stored in a linearly scaled format, even if a logarithmic

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format is selected for the display. The data is saved in either a tab-delimited or comma-delimited format which can be opened by most data analysis software.

3. Graphical Display

3.1 Graph Types

3.1.1 Apodization Profile

This graph displays the apodization profile applied to the grating. The profile is applied by multiplying the refractive index changes by the apodization values.

3.1.2 Phase Profile

This graph displays the phase profile along the grating. The phase corresponds to changes in the grating pitch. A grating with a constant pitch will not have any pitch phase change. The pitch is calculated based on the distance between the same numbered peaks in a chirped grating compared to an un-chirped grating. Figure 2 shows how the grating phase is calculated from the refractive index profiles of a chirped and un-chirped grating.
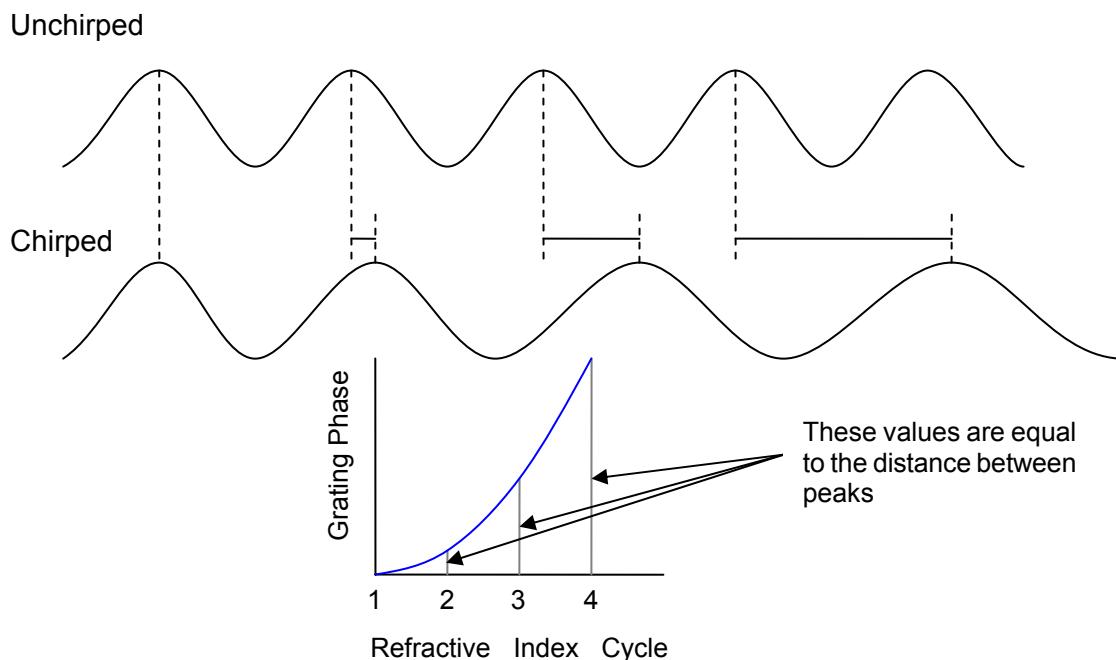
Figure 2: Graphical demonstration of the calculation of phase for a chirped grating

3.1.3 Refractive Index Profile

This graph displays the refractive index profile along the length of the grating. Due to the small period of the index change variations the Grating Length Step parameter must be set to a small value, less than the phase mask pitch, to see useful detail in this graph.

The phase mask pitch is the width of the relief structure of the phase mask used to write the grating. It is twice the pitch of the resultant grating.

3.1.4 Coupling Coefficient Profile

This graph displays the coupling coefficient profile. The coupling coefficient is a complex number with an absolute value equal to the refractive index envelope and an argument which is dependent on the grating phase.

3.1.5 Reflection Coefficient Profile

This graph displays the profile of the reflection coefficient along the length of the grating. This coefficient determines the amount and the phase of reflected light at a given point on the grating.

3.1.6 Reflectance Coefficient (Spectrum)

This graph displays the amplitude of the reflection coefficient from the grating as a function of wavelength.

3.1.7 Reflectivity Spectrum

This graph displays the reflectivity spectrum from the grating as would be detected by an optical spectrum analyser.

3.1.8 Reflectivity Phase (Spectrum)

This graph displays the phase of the reflection spectrum. It is equal to the argument of the Reflectance Coefficient.

3.1.9 Group Delay (Spectrum)

This graph displays the group delay spectrum of the grating. As the group delay is dependant of the gradient of the Reflectivity Phase, sudden phase shifts will cause a very large Group Delay value at that point.

3.1.10 Interference Spectrum

This graph displays the result of interfering the grating reflection spectrum with an ideal laser beam. The relative strength and phase of the beam can be changed using the simulation properties.

3.1.11 Zooming In

The graph can be zoomed in on a section to view it in greater detail by dragging a rectangle around the region using the mouse.
The zoomed/magnified view can be shifted by holding the Shift key and dragging the mouse. When the mouse button is released the view will shift. To return to the original view hold the Control key and click anywhere on the graph.

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In the Graph menu is the option to Show Zoom Overview. Selecting this option will display a small window showing a reduced image of the graph with the current view highlighted by a black box. This is to help navigate the graph while zoomed in.

3.1.12 Complex Variables

The Refractive Index Profile, Coupling Coefficient Profile, Reflection Coefficient Profile and Reflectance Coefficient graphs display complex variables. A drop-down list in the top-right corner of the graph can be used to change the way the data is displayed.

The four choices are to graph the real part, the imaginary part, the absolute value or the argument. If the argument is displayed then an additional option will be displayed to the left which will un-wrap the phase if desired. Un-wrapping the phase will remove all 2π radian jumps in the data. These jumps are caused by the inability of the arctan function to represent continuously phase changes beyond the range $\pm\pi$.

4. Simulator Parameters

4.1 Laser Parameters

The parameters *Laser Power* and *Writing Speed* are combined to compute the energy per unit length the fibre is exposed to. This exposure is then converted to a refractive index change using the calibration data for the chosen fibre.

4.1.1 Laser Power

This sets the power of the writing laser. A higher Laser Power will create a larger refractive index change.

4.1.2 Loss Factor

This sets the fractional amount of laser power lost. A value of 0 indicates that no power is lost. A value of 1 indicates all the power is lost and none reaches the fibre. This factor can be used as well to compensate for optics introduced into the writing assembly which may affect the power of the beam at the fibre.

4.1.3 Minimum Power

This sets the minimum percentage of beam power which the fibre will be exposed to. This is also the relative strength of the tails compared to the body of the fibre. Grating tails are short sections of fibre at either extreme of the grating which are exposed to the laser to have the same effective refractive index as the rest of the grating without any index variation structure.This parameter is applied by setting the lower limit of the apodisation profile and will affect the apodisation profile graph.

4.1.4 Writing Speed

This sets the speed at which the laser beam scans along the fibre during the writing process. A slower speed will result in a longer exposure time causing a larger refractive index change.

4.1.5 Power Compensation

The Power Compensation dialog allows either the Laser Power or Writing Speed to be changed while maintaining a fixed energy per fibre length, in order to produce the same index change. To use this tool, click on the Power Compensation button. This will open a window where either the power or speed can be varied and then when the calculate button is selected, the corresponding speed or power to maintain the existing energy per unit length will be calculated.

4.2 Fibre Parameters

4.2.1 Fibre Type

This selects the fibre type of the simulated grating. Different types of fibres may respond differently to applied strains and to the laser energy. For more information about fibre types see the "Fibre Types" section.

4.2.2 Phase Mask Pitch

This sets the pitch of the phase mask used to write the grating. The phase mask used determines the centre wavelength at which the grating will reflect, although this may be affected by additional parameters.

4.2.3 Grating Length

This is the length of the grating, excluding the tails. Longer gratings tend to have a narrower reflection spectrum and will generally have a higher reflectivity.

4.2.4 Writing Strain

This sets the strain applied to the grating while it is being written. When the writing is completed the strain is removed and the grating relaxes, causing the pitch to reduce slightly. This in turn causes the peak wavelength to be lowered.

4.2.5 Grating Tail Length

Grating tails are short sections of fibre at either extreme of the grating which are exposed to the laser to have the same effective refractive index as the rest of the grating without any index variation structure..

4.2.6 Chirp

A chirp is a gradual variation in the pitch of the phase mask along its length. This has the effect of increasing the reflection bandwidth of the grating. There are two types of chirp which can be applied, linear and quadratic.

4.2.7 Use Index Profile

This selects whether a custom index profile is used. If a custom profile is used then it is added on to the refractive index profile created by the laser. To use purely the values specified in the profile, set the Laser Power parameter to 0.

4.2.8 Use Pitch Profile

This selects whether a custom pitch profile is used. If a custom profile is used then the pitch modifications are added to those calculated from the phase mask and the chirp parameters.

4.3 Apodization Parameters

4.3.1 Apodization Type

This selects the type of apodization used on the grating. Apodizing the grating reduces the size of the side-lobes surrounding the central peak reflection.

4.3.2 Apodization Order

The apodization order, in most cases, is the power to which the apodization profile is raised.

4.3.3 Constant n_{eff}

If this option is selected then the apodization profile will be applied in a way which prevents the effective refractive index of the material from changing. If the effective index changes then the reflection bandwidth may increase as changing the effective index effectively changes the pitch of the grating.

4.4 Additional Parameters

4.4.1 Additional Apodization Parameters

Some apodization profiles may have additional parameters, which will appear at the bottom of the application window. Holding the mouse over each parameter will display a tip showing the allowed range.

4.4.2 Start Wavelength & End Wavelength

These are the wavelengths at which the output reflection spectrum starts and ends. Depending on whether the Relative to Grating Centre checkbox is selected these values will be either absolute wavelengths or relative wavelengths.

4.4.3 Relative to Grating Centre

This determines if the start and end wavelengths are relative to the centre wavelength. The centre wavelength is calculated using the phase mask and strain parameters.

Applying a chirp or custom pitch profile to a grating may change the wavelength of the reflection peak. These changes are not taken into account and may cause the reflection peak to shift off the graph.

4.4.4 Interference Beam

The interference beam is used to simulate the result of a Bragg grating fibre interferometer as shown in Figure 3.
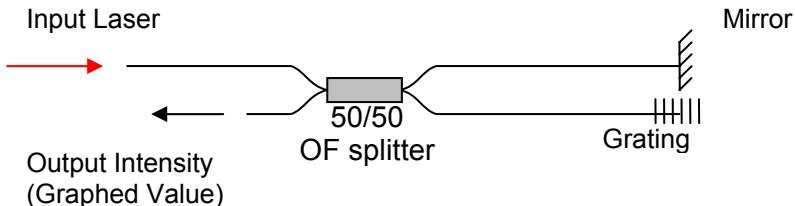
Figure 3: Schematic diagram of the fibre interferometer used to simulate interference spectra

4.4.4.1 Phase
This sets the relative phase of the interfering beam.

4.4.4.2 Strength
This sets the relative strength of the interfering beam. This is equal to the mirror's reflectivity in Figure 3.

4.4.5 Grating Length Step

This sets the width of the slices the grating is broken up into for simulation.
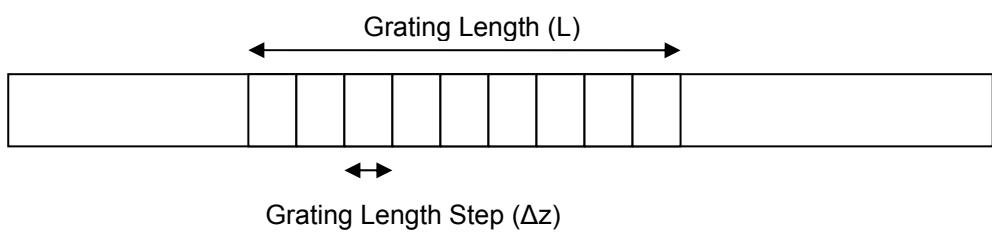
Figure 4: Schematic Diagram representing Grating Length Step division

4.4.6 Wavelength Step

This sets the resolution of the output reflection spectrum.

4.4.7 Simulate

This runs the simulation. Clicking this button again while the simulation is running will cancel it.

4.4.8 Simulate Reflectance

This determines whether the reflection spectrum is calculated or not.

5. Profile Editing

5.1 Moving Points

Points in a profile can be moved by dragging them with the mouse. By dragging a rectangle around multiple points, the whole group can be moved as a whole. Points selected into a group will change colour to pink. Points can be added or removed from the group by holding the Shift key and clicking on them.

A point may not be moved past its left or right neighbours. Additionally the points at 0% and 100% cannot be moved horizontally.

A single point can be selected by clicking on it, this will change its colour to red. The position of this point can then be altered by changing the Selected Position parameters.

5.2 Adding & Deleting Points

A point can be added to a line by holding the Control key and clicking on the line. While Control is being held a small circle will highlight the position the new point will be created at.

Attempting to create points on particularly steep lines may not always work. The easiest way to overcome this problem is to zoom in on the region where the point is to be created.

To delete a point hold the Control key and click on it.

5.3 Zooming & Scale

Zooming in the profile editor window is quite similar to zooming in the main graph with a few minor differences. To zoom in on a region hold the Control key and drag a rectangle around the region of interest. To zoom back out hold the Control key and click in a blank (white) area of the editor. Be careful not to click on a point while holding the Control key as this will delete it.

To move the view while zoomed in, hold the Shift key and drag the mouse. However this must not be done on a point as it will instead move the point. The scale of the graph sets the largest range of values which can be viewed. It is possible to zoom in and show a smaller range in more detail but to zoom back out the scale must be changed.

The horizontal scale is fixed between 0% and 100% however the vertical scale can be changed using the Scale section on the left bar. To change the scale, type the new minimum and maximum values in the appropriate box and click the Set button. Clicking the Reset button will return the scale to its default range.

5.4 Saving and Loading Profiles

Profiles can be saved and loaded through the File menu. Profiles are saved with either .ip or .pp extensions for index and pitch profiles respectively. The profile editor is able to open standard tab-delimited files provided that there are only numbers in the file and all values in the first column are between 0 and 100.

6. Comparing Spectra

The simulation results can be compared against experimental data or the saved results of a previous simulation. Only the Reflectivity Spectrum can be compared. The data being compared against will show up on this graph in green.

6.1 Importing Data

In order to compare the data it must first be imported into the simulator. This is done through the Comparison tab, located at the top of the graph area.

To import the data click the Import… button and select the file which contains the data. It is also important to select the right type of file using the Files of Type list.

Several file formats may have a similar extension, such as *.txt for text files, so make sure the correct format is selected in the dialog box otherwise the file will not load correctly.

Once the data is imported, a message with any additional information about the file will appear in the top text box. If the simulator has been run and produced an output then a comparison between the imported data and the simulation results will be displayed in the bottom text box. This compares the peak reflectivity, the wavelength of this peak and the full width at half maximum (FWHM) of the peak.

If the imported data is no longer required for comparison it can be removed by clicking the Clear button.

6.2 Wavelength Clipping

When data is imported and displayed in the reflectivity spectrum graph the whole wavelength range is displayed. This may be much larger than the region of interest. The imported data can be clipped to a certain wavelength range. When data is clipped, using the Apply button, only wavelengths which fall between the start and end wavelengths specified will be displayed.

6.3 Saving Imported Data

Imported data can be re-saved as either a standard tab or comma separated text file. This is done by selecting the Save Imported Data… command from the File menu while in the Comparison tab.

Any wavelength clipping applied to the imported data will also apply when it is saved. This means only what is visible in the reflectivity spectrum graph will be saved to the file.

7. Managing Variables

Different optical fibres have different photosensitivity levels and strain-optic coefficients. The simulator lets you create calibration data for many different fibres to account for these differences. All Fibre Type functions are found in the Fibre Settings window accessible through the Fibre Types… item in the Settings menu.

7.1 Creating New Fibre Types

To create a new Fibre Type press the Create button under the list of existing types. This will create a new fibre.
Once the Fibre Type has been created the first step is to name it. Enter the name of the fibre in the Fibre Name box at the top of the screen.
Once the calibration of the fibre type is completed the data must be saved by pressing the Save or Save As… button.

7.2 Calibrating Fibres

To calibrate a built-in fibre a copy of the fibre must first be made by selecting the fibre and pressing the Make Copy button. Once the copy is created its calibration can be updated.

7.2.1 Strain Calibration

Strain calibration is used to convert the strain a fibre is placed under into a wavelength shift of the reflection spectrum. Each phase mask for which data is entered has its own set of strain coefficients. If a phase mask is simulated which does not have a set of coefficients, the coefficients will be interpolated from the two closest matches.

7.2.2 Requirements

The data required for each fibre is:
- Phase Mask Pitch
- Writing Strain
- Reflection Centre Wavelength

To perform a strain calibration there must be at least two, un-chirped, fibres written at different strains per phase mask. Ideally all phase masks to be used should be calibrated but the simulator will attempt to interpolate data for non-calibrated phase masks.

The writing power and apodization profiles used should have a negligible impact on the grating wavelength and are ignored during calibration. The fibres must not have any chirp or other variations in the grating pitch as this will affect the wavelength and cause incorrect calibration.

7.2.3 Data Entry

To begin a strain calibration, click the top Calibrate button. This will bring up the data entry screen.

Press the Add button or double-click the Add New Entry… option in the list to the left to create a new entry. This entry will appear in the list and can now be edited.

To enter the data into the new entry click on one of the numbers and enter the appropriate experimental value. The Tab key can be used to move to the next value.

A specific entry can be removed by selecting it and pressing the Delete button. To remove all entries use the Clear… button.

Note that changes are not saved unless the calibration process is run or the Save data button is pressed.

To continue to the calibration stage press the Next Step button. The data entered can be saved without calibrating, for use later, by pressing the Save Data button or pressing the Back button and selecting the Yes option.

7.2.4 Calibrating

Once the Next Step button is pressed the calibration graph is shown. This graph attempts to perform a linear fit on the data by first grouping it by phase mask.
Any phase mask with only one data point entered will not be calibrated as it is not possible to fit a line to a single point.

From the supplied data each of the following values are calculated:
- The refractive index of the fibre
- The calibration factor of the fibre at each phase mask. This is a measure of how much a strain will affect the reflection wavelength.
- A wavelength adjustment for each phase mask. This is a constant adjustment which accounts for slight variations in the actual phase mask pitch.

All these parameters can be manually edited and pressing the Enter key will update the graph.

The calibration button will recalculate the calibration constants using the currently selected phase mask as the base. Changing the base has an effect only on the refractive index. When the calibration is completed press the Done button. The strain calibration parameters, including the phase masks, will be saved to the fibre type.

7.3 Energy Calibration

Energy calibration is used to convert the laser energy into a refractive index change. This simulator is only able to perform a linear fit to the stored experimental data, which becomes less accurate as the laser energy increases.

7.3.1 Requirements

The data required for each fibre are:

- Laser Power
- Writing Speed
- Fibre Length
- Fibre Peak Reflectivity

At a minimum calibration requires data sets for two fibres, although the more data sets available the more accurate the calibration will be.

All the fibres to be calibrated must have the same apodization profile. The profile information is required to account for the changes in reflectivity caused by the apodization. Other than the apodization the fibres should not have any other changes to the index profile. The fibres must also be un-chirped as chirping broadens the reflection spectrum and lowers the peak value.

7.3.2 Data Entry

The data entry procedure for energy calibration is similar to the procedure for strain calibration.

Begin by adding a new entry. This is done by either double-clicking the Add New Entry… item in the list or pressing the Add button.

Once an entry is added, click on the individual elements and type in the appropriate values. The Tab key can be used to move to the next value.

The reflectivity can be entered as either a fraction or in dB. This is set using the Scale setting to the right of the application window. When this is changed the existing reflectivity values will be automatically converted. Note that this may cause minor rounding errors if the scale is changed and then changed back again.

The apodization profile used to write the fibres must also be entered. This must be the same for all fibres entered.

Entries can be removed using the Delete and Clear… buttons. Any changes made can be saved without calibrating by using the Save Data button or by pressing the Back button and choosing the Yes option.

Once all data is entered press the Next Step button.

7.3.3 Calibration

Calibrating the energy coefficient may take some time. Once it is completed a graph will be displayed showing the index change produced for a given energy intensity.

The calibration process will try to perform a linear fit on this data. However for high intensities or for fibres with a high photosensitivity the trend is generally non-linear.

The calibration factor can be manually altered. Pressing the Enter key will update the graph.

When the calibration is complete press the Done button to save the calibration data.

7.3.4 Managing Fibre Types

Fibre types are displayed in the Fibre Type list with several different formats. A fibre in normal text is a user defined type loaded from a file. A fibre in bold text has been altered and not yet saved. If the simulator is exited the changes will be lost.

Built in fibre types will appear in the list provided there is not a user defined type with the same name.

Fibre types can be deleted using the Delete button. This occurs immediately, unlike most other operations on fibre types, and cannot be undone.

A fibre type can be shared, without including the experimental data used to calculate the calibration coefficients, by selecting the fibre and pressing the Remove Data button. Removing the experimental data will have no effect on the simulated results using the fibre type. However it can't be incrementally updated with new experimental data. The fibre type must be saved to actually remove the data.

8. Acknowledgements

Appendix A: Formulae for Apodization Profiles

The formula used for each apodization profile is given below. The variables z, L and n correspond to the position along the grating of a point, the length of the grating and the apodization order respectively.

8.1.1.1 None (Flat):
$$A(z) = 1$$

8.1.1.2 Cos Squared:
$$A(z) = \cos\left(\pi \frac{z - L/2}{L}\right)^{2n}$$

8.1.1.3 Blackman-Harris:
$$\omega = \frac{2\pi z}{L}$$
$$A(z) = \left(0.35875 - 0.48829\cos(\omega) + 0.14128\cos(2\omega) - 0.01168\cos(3\omega)\right)^{n}$$

8.1.1.4 Hanning:
$$A(z) = \left(0.5 + 0.5\cos\left(2\pi \frac{z - L/2}{L}\right)\right)^{n}$$

8.1.1.5 Sinc Squared:
$$A(z) = \left(\operatorname{sinc}\left(\pi \frac{2z - L}{L}\right)\right)^{2n}$$

8.1.1.6 Super Gaussian:
$$w = \text{FWHM}$$
$$A(z) = \exp\left[-\ln 2 \times 2\left|\frac{z - L}{2w}\right|\right]^{2n}$$

8.1.1.7 Flattened Cosine:
$$A(z) = 0.25\cos\left(\frac{2\pi z}{L} + \pi\right)^{n}$$

8.1.1.8 Blackman-Harris 2 (Writing System):
$$\omega = \frac{2\pi z}{L}$$
$$A(z) = \left(0.42323 - 0.49755\cos(\omega) + 0.07922\cos(2\omega)\right)^{n}$$

Appendix B: Definition of Variables

B.1. Parameter Definitions

These are parameters set by the user:

a – Fibre Wavelength Adjustment
C_L – Linear Chirp
C_Q – Quadratic Chirp
E – Fibre Energy Coefficient
Λ_0 – Phase Mask Pitch
L – Length of Grating (excludes tails)
L_T – Length of Tail

v – Laser Write Speed
n_0 – Fibre Refractive Index
$\Delta P(z)$ – Custom Pitch Profile
P_L – Laser Power
s – Fibre Writing Strain
S – Fibre Strain Coefficient
Δz – Grating Length Step

B.2. Simulation Variable Definitions

$A(z)$ – Apodization Profile
δ – Wavelength Detuning Parameter
$\phi(z)$ – Phase Profile
$g(\lambda)$ – Group Delay Spectrum
$K_0 = 2\pi/\Lambda_0$
$K_P(n)$ – Array of K values of refractive index modulation peaks.
λ – Wavelength
λ_0 – Peak Reflection Wavelength (Doesn't include Chirp & Custom Pitch Profile)
m – Minimum Power
$n(z)$ – Refractive Index Profile
$n_{eff}(z)$ – Effective Refractive Index of Fibre after writing
$\Delta n(z)$ – Envelope of Refractive Index Change Profile

$\Delta n_C(z)$ – Custom Refractive Index Profile
$P(z)$ – Grating Pitch Profile
$q(z)$ – Coupling Coefficient Profile
$\rho(z)$ – Reflection Coefficient Profile
$r(\lambda)$ – Reflectance Coefficient Spectrum
z – Position along Grating.
   $z = -L_T$ corresponds to start of first tail
   $z = 0$ corresponds to start of grating.
   $z = L$ corresponds to end of grating
   $z =: L + L_T$ corresponds to end of final tail
$z_P(n)$ – Array of z values of refractive index modulation peaks

B.3. Simulation Sequence Formulae

Listed below are the formulae used to simulate the reflection spectrum of the grating.

B.3.1 Peak Wavelength

$$\lambda_0 = n\Lambda_0 + sS + a$$

B.3.2 Apodization

$$A(z) = m + A(z)(1-m)$$

$$A(z) = \begin{cases} \text{Output of Apodization Function} & 0 \leq z \leq L \\ 0 & 0 > z > L \end{cases}$$

B.3.3   Refractive Index Change

$$\Delta n(z) = \frac{P_L}{v} E \cdot A(z) + \Delta n_C(z)$$

B.3.4   Effective Refractive Index

$$n_{eff}(z) = \begin{cases} n_0 & \text{for constant } n_{eff} \\ n_0 + \dfrac{A(z)\Delta n(z)}{2} & \text{for non - constant } n_{eff} \end{cases}$$

B.3.5   Grating Phase

p – Refractive index modulation peak number

K – Grating 'wave number' $= \dfrac{2\pi}{\Lambda}$

$P(z) = zC_L + z^2 C_Q + \Delta P(z)$

$z = 0, p = 1$

while $(z < L)$

{

    $z = z + P(z)$

    $z_P(p) = z$

    $K_P(p) = \dfrac{2\pi p}{z}$

    $p = p + 1$

}

K – Value of K interpolated to the value of z from the z_P and K_P arrays.

$$\phi(z) = \begin{cases} \dfrac{z(K - K_0)}{2} & 0 \leq z \leq L \\ 0 & z < 0 \\ \phi(L) & z > L \end{cases}$$

B.3.6   Refractive Index Profile

$$n(z) = n_0 + \frac{\Delta n(z)}{4} \exp(i(zK_0 + \phi(z)))$$

B.3.7   Coupling Coefficient Profile

$$q(z) = \frac{-iK_0 \Delta n(z)}{4n_{eff}(z)} \exp(-i\phi(z))$$

B.3.8   Reflection Coefficient

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$$\rho(z) = \frac{-q(z)^* \tanh(|q(z)|\Delta z)}{|q(z)|}$$

B.3.9 Reflectance Coefficient

$\mathbf{P}(z, \lambda)$ – Propagation Matrix
$\mathbf{R}(z)$ – Reflection Matrix
$\mathbf{T}(\lambda)$ – Transmission Matrix

$$\delta(\lambda, z) = \frac{2\pi n_{eff}(z)}{\lambda} - \frac{K_0}{2}$$

$$\mathbf{P}(z, \lambda) = \begin{bmatrix} \exp(i\delta(\lambda, z)\Delta z) & 0 \\ 0 & \exp(-i\delta(\lambda, z)\Delta z) \end{bmatrix}$$

$$\mathbf{R}(z) = \sqrt{1 - |\rho(z)|^2} \begin{bmatrix} 1 & -\rho(z)^* \\ -\rho(z) & 1 \end{bmatrix}$$

$$\mathbf{T}(\lambda) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$z = -L_T$
while $(z \leq L + L_T)$
{

   $\mathbf{T}(\lambda) = \mathbf{T}(\lambda)\mathbf{P}(z, \lambda)\mathbf{R}(z)$

   $z = z + \Delta z$

}

$$r(\lambda) = \frac{\mathbf{T}(\lambda)_{21}}{\mathbf{T}(\lambda)_{11}}$$

B.3.10 Group Delay

$$g(\lambda) = \frac{\lambda^2}{2\pi c} \frac{d \arg(r(\lambda))}{d\lambda}$$

B.4. Displayed Values

Listed below are the various graph types available. For each graph the quantities graphed along the x and y axes are given.

B.4.1 Apodization Profile

$x \leftarrow z$
$y \leftarrow A(z)$

B.4.2 Phase Profile

$x \leftarrow z$
$y \leftarrow \phi(z)$

B.4.3 Refractive Index Profile

$x \leftarrow z$
$y \leftarrow n(z)$

B.4.4 Coupling Coefficient Profile

$x \leftarrow z$
$y \leftarrow q(z)$

B.4.5 Reflection Coefficient Profile

$x \leftarrow z$
$y \leftarrow \rho(z)$

B.4.6 Reflectance Coefficient

$x \leftarrow \lambda$

B.4.7 Reflectivity Spectrum

$x \leftarrow \lambda$
$y \leftarrow |r(\lambda)|^2$

B.4.8 Reflectivity Phase Spectrum

$x \leftarrow \lambda$
$y \leftarrow \arg(r(\lambda))$

B.4.9 Group Delay Spectrum

$x \leftarrow \lambda$
$y \leftarrow g(\lambda)$

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19. ABSTRACT

This document is a user manual for a software application that predicts the complex reflection spectrum of fibre Bragg gratings, given user defined input parameters. The software is designed primarily to complement the joint DSTO/Swinburne grating writing facility (FigFab) and can be used to determine the optimum writing variables to achieve a required grating reflection profile. Alternatively the software can be used to simulate the intensity and phase information for use in other Bragg grating sensing applications such as intragrating strain profiling.